

# Scalable multiparticle entanglement of trapped ions



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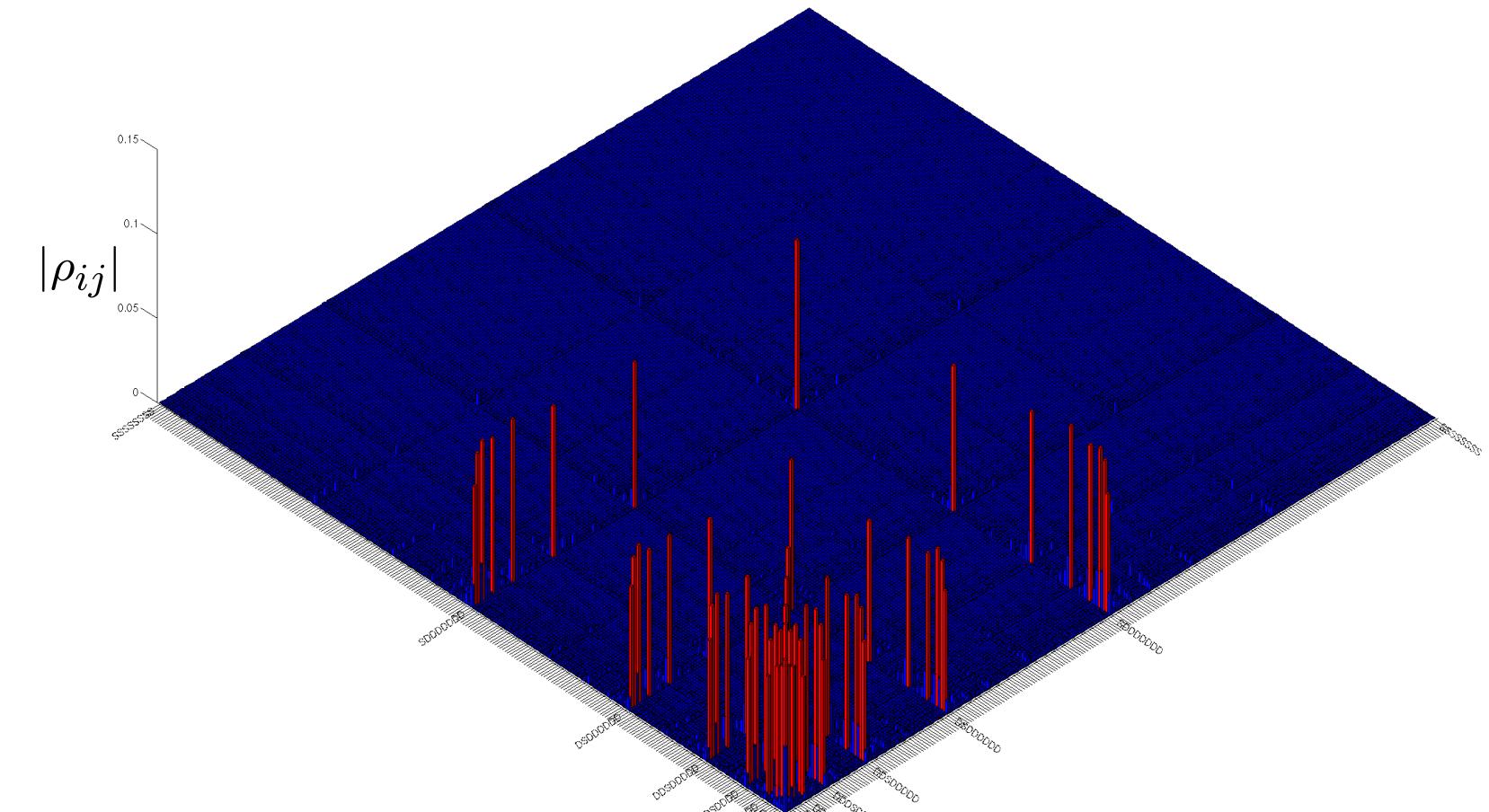
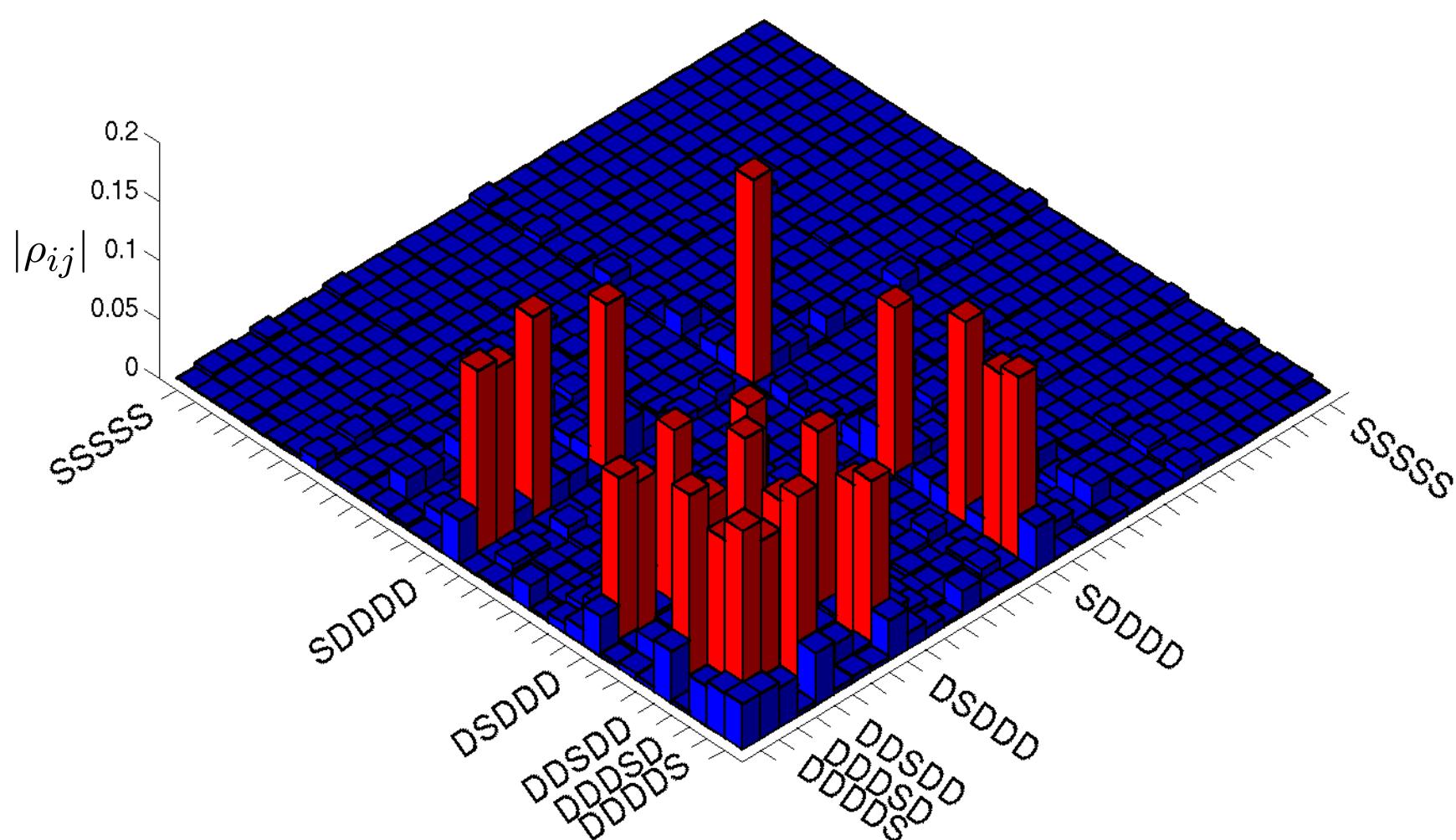


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## Introduction

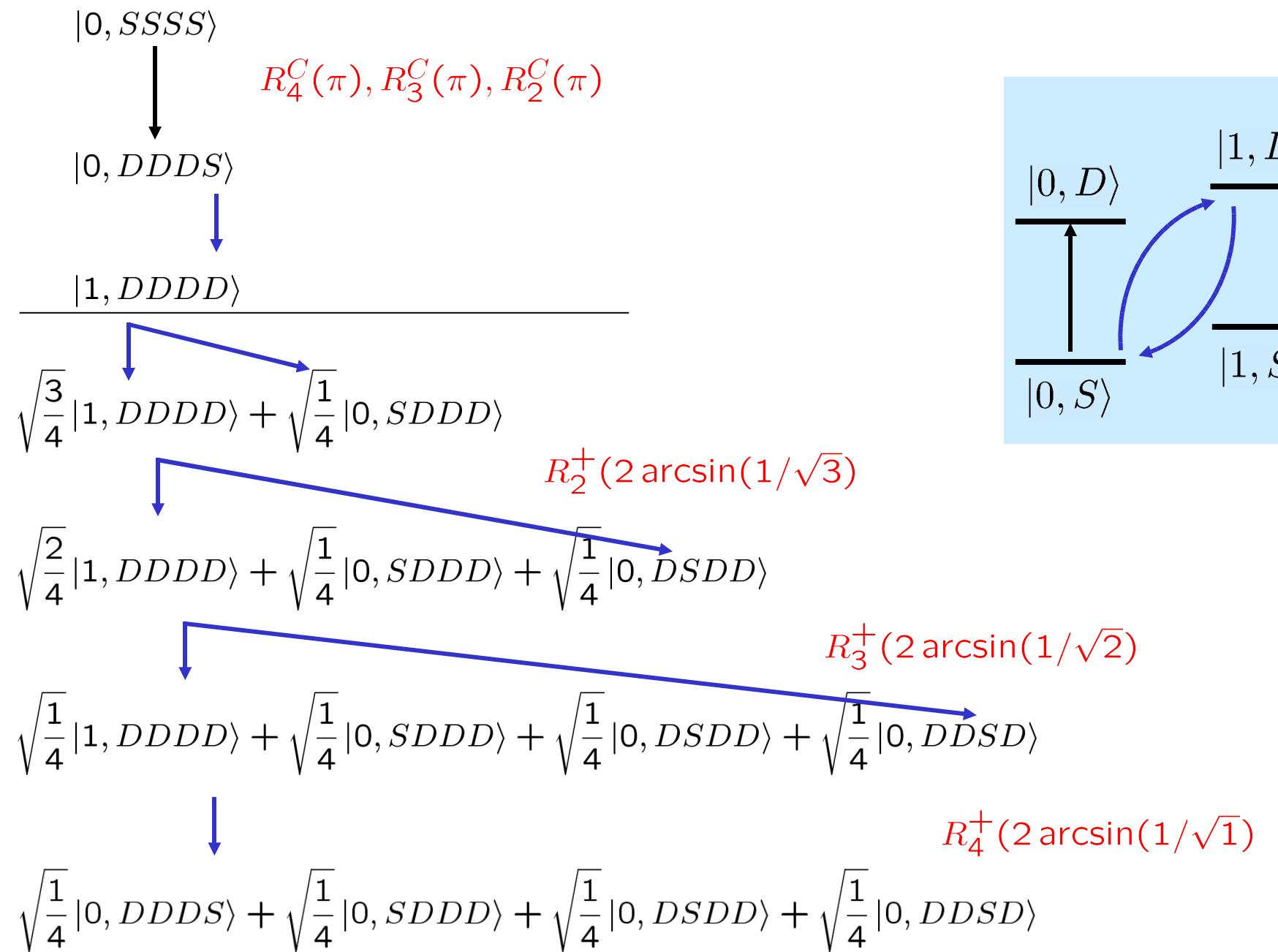
Individual entangled particles are not independent of each other and their quantum properties are inextricably interwoven. Consequently, the intriguing features of entanglement become particularly evident if the particles can be individually controlled and physically separated. Among the various kinds of entangled states, the W-state plays an important role since its entanglement is maximally persistent and robust even under particle loss. Here we report on the scalable and deterministic generation of four-, five-, six-, seven- and eight-particle W-states with trapped ions. We obtain the maximum possible information on these states by performing a full characterization via state tomography using individual control and detection of the ions. Moreover, we prove in a detailed analysis that they carry genuine four-, five-, six-, seven- and eight-particle entanglement, respectively. The availability of such multiparticle entangled states together with the full information in form of their density matrices creates a test-bed for theoretical studies of multiparticle entanglement.



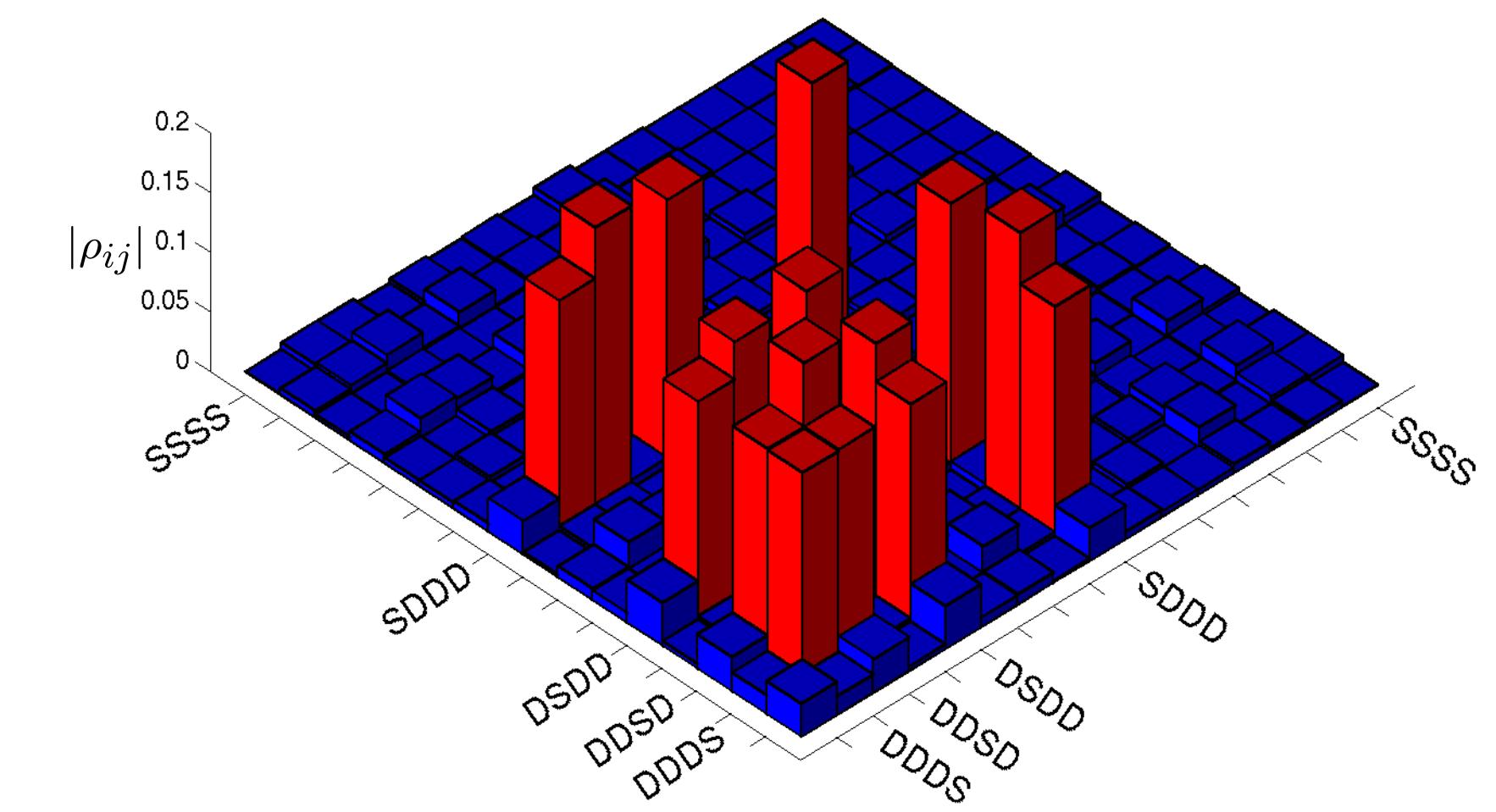
## Is there entanglement?

- Negative expectation value of the entanglement witness  
=> genuine multiparticle entanglement.
- Positive bipartite concurrence (after projection onto  $|0\rangle\langle 0|_i$ )  
=> any (N-particle entangled) state can be distilled out of a lot of copies with local operations and classical communication.

## Generation of W-states



## Measured density matrix



## Some interesting quantities

N	Fidelity	Witness	Min(Concurrence)
4	0.85	-0.46(3)	0.76(3)
5	0.78	-0.20(3)	0.61(2)
6	0.79	-0.27(3)	0.57(2)
7	0.76	-0.07(3)	0.59(1)
8	0.72	-0.03(1)	0.54(1)

## Experimental imperfections for a $W_6$ -state

Addressing error: 0.1  
Off-resonant excitations: 0.04  
(taken care by pulse shaping)  
Laser frequency noise: 0.07  
Ground state cooling: < 0.03  
Optical pumping: 0.02/Ion  
(taken care by state-preparation verification)

Simulation carried out for the  $W_6$ .

## Some further numbers

- For the measurement  $3^N$  measurement settings are required.
- Every 20 ms another W-state. Simulation with matlab takes 20 minutes (Hilbert space: 8–two level systems + {0,1,2} phonons of the bus-mode).
- Over 10 hours measurement time for the  $W_8$  – state.
- Reconstruction of the density matrix from the data takes about a week on a fast desktop-computer (scaling  $\sim 24^N$ ).

Use an iterative procedure:

$$\rho_{n+1} = R_n \rho_n R_n$$

$$R_n = \sum_{i,\alpha} \frac{f_i}{\langle y_{i,\alpha} | \rho_n | y_{i,\alpha} \rangle} |y_{i,\alpha}\rangle \langle y_{i,\alpha}|$$

$f_i$ : measured expectation values

$|y_{i,\alpha}\rangle$ : projectors on the measurement bases

Accelerate convergence by fitting and extrapolation ( $\epsilon$  algorithm).

## Reconstruction procedure